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PERSISTENT TIME INTERVALS BETWEEN FEATURES IN SOLAR FLARE HARD X-RAY EMISSION

Upendra D. Desai and Chryssa Kouveliotou

Laboratory for Astronomy and Solar Physics
NASA Goddard Space Flight Center

C. Barat, K. Hurley, M. Niel, R. Talon, and G. Vedrenne

Centre d'Etudes Spatiale de Rayonnment
Toulouse, France

Abstract

Several solar hard X-ray events (> 100 keV) have been observed simultaneously with identical instruments on the Venera 11, 12, 13, 14 and Prognoz spacecraft. High time resolution (= 2 ms) data were stored in memory when a trigger occurred. We present the observations of modulation with a period of 1.6s for the event on 1978 December 3. We also present evidence for fast time fluctuations from an event on November 6, 1979, observed from Venera 12 and another on September 6, 1981, observed from the Solar Maximum Mission. We have used power spectrum analysis, epoch folding, and Monte Carlo simulation to evaluate the statistical significance of persistent time delays between features. The results are discussed in light of the MHD model proposed by Zaitsev and Stepanov (Soviet Astron. Letters, 1982, 8, 132, and Solar Physics, 1984, 92, 283).

1. Introduction

Light curves of a number of solar flare events observed in microwaves and/or X-rays with high time resolution ($\sim$ 0.1 s) show distinctive features during the rise and/or decay phases. The time histories of hard X-rays observations with time resolution of about a second on TD-1A could be resolved into "elementary flare bursts" with full width at half maximum of 4 to 25 s (van Beek 1974, de Jager and de Jonge 1978). The study of a number of such elementary flare bursts in a single event or their distribution in time was not pursued in earlier papers. Recently, Loran et al. (1985) have simulated the fast ripple structure by incorporating in their model a variable repetition rate of these elementary bursts. Sturrock et al. (1984) have tried to associate elementary event bursts

with "elementary flux tubes", thus suggesting that the features are spatial in origin. However, Ohki (1985) reports from Hinotori imaging data that the small size of the sources of impulsive flares and the lack of motion indicate that spikes are temporal rather than spatial in origin, i.e. that the same flux tube flares repeatedly.

Pioneering observations of solar hard X-rays (> 20 keV) by Parks and Winckler (1969) with a balloon-borne detector revealed significant power at a period of 16 s. They also reported similar simultaneous behavior in microwaves at 15.4 GHz. Frost (1969) reported the existence of modulation in OSO-5 data with a period of 35 s. Rosenberg (1970) analysing the solar radio event of February 15, 1969 (160-320 MHz), reported modulations with a period of 1 s. He explained the modulations on the basis of magnetohydrodynamic (MHD) oscillations in a coronal magnetic flux tube. Janssens et al. (1973) also reported periodicities in radio data. In two homologous microwave events on May 29, 1980, Urpo (1983) has reported features with an average separation of 3.04 s. Recently Zodi et al. (1984) have reported 1.5 s pulsations in both 22 GHz and 44 GHz high time resolution microwave data. Wiehl and Matzler (1980) studied both hard X-ray and microwave events and reported the existence of quasi-periodic modulations with periods as short as five seconds. In their study a change of slope during the rise or fall was accepted as a modulation feature.

In the studies mentioned above emphasis has been given on results that demonstrate periodicities or quasi-periodicities. We present solar events which show the prevalence of persistent time-delays between successive or alternate features indicative of the existence of a synchronized series of features. We examine this in the light of the proposed MHD model of Zaitsev and Stepanov (1982, 1984). Various models have been proposed to explain pulsations both in hard X-rays and in radio data (Rosenberg 1970, McClean et al. 1975, Chiu 1970).

Power spectrum analysis of transient events to find out periods which are fractions of the total duration of the transients are not adequate. We have also pursued auto correlation, the epoch-folding technique, and Monte-Carlo stimulation to statistically evaluate the persistence of delay times between features. In highly dynamic turbulent phenomena like solar flares, strict periodicities may not prevail but parameter dependent characteristic times - rise, decay, and delay times - could prevail.

2. Observations

Observations reported here were made on the Venera 12 deep space probe (V_{12}) and the Earth orbiting Solar Maximum Mission (SMM) satellite. Detailed discriptions of the instrumentation have appeared in Barat et al. (1981), Chambon et al. (1979), and Orwig et al. (1980). The basic detectors on V_{12} are 4.5-cm radius, 3.7-cm thick NaI(Tℓ) scintillators with a

plastic anticoincidence shield; the Hard X-Ray Burst Spectrometer (HXRBS) on SMM consists of a CsI(Na) scintillator surrounded by a CsI(Na) shield with an opening angle of $\sim 40°$ FWHM. In both detectors, an increase in counting rate above a certain threshold initiates data storage in memory. The finest time resolution available is 2 ms for V_{12} and 1 ms for SMM. The average photon energy threshold is $\sim$ 100 keV for V_{12} and $\sim$ 30 keV for SMM. For the present study data with 109 ms and 15 ms integration are used for V_{12} and 128 ms for SMM data.

The Event on 1978 December 3

On 1978 December 3 at 20^h30^m UT, an Hα flare of importance SB was observed from McMath region 15694 located at S22E65. Figure 1 shows the time history of the hard X-rays observed from V_{12} with 109 ms resolution. V_{12} was closer to the Sun than Earth-orbiting spacecraft and consequently had better statistics. The total duration of the event was 16 s with the maximum counting rate occurring 9 s from the start. Significant temporal variations are seen during the rising phase. The filtered data are shown at the bottom of Figure 1 with the times of various statistically significant peaks indicated. Two series of peaks with delay times of about 1.6 s are indicated in the figure. Figure 5 shows the histograms of the delay times between alternate features. The amplitude of the pulses of the first series appears to be constant while the amplitude of the second series of pulses is growing. The average pulse profile after proper phase folding for 6 cycles is also indicated in Figure 4a. The shape of the first series of pulses is symmetrical with rise and decay times of about 300 ms. The time-varying second series of pulses is poorly defined statistically. During the decay phase after about 11 s, the pulsations are significantly attenuated.

Bogovalov et al. (1983) have analysed several solar events for quasi-periodicities and have reported for this same 1978 December 3 event pulsation frequencies of 1.22 ± 0.03 Hz and 0.50 ± 0.03 Hz with 99% confidence limits. We have also carried out the power spectrum analysis and agree with their results, but to emphasise the existence of two synchronised series of features, we have also used the epoch-folding technique and evaluated the χ^2 for various periods. We found that χ^2 peaks at a period of 1.64 s.

The light curve of this event shows a succession of ten prominent peaks. The times of occurrence of all ten peaks can be described as a periodic series of seven peaks with an "inter-pulse" which occasionally appears at a stable phase. The probability of the peaks happening with this arrangement can be calculated by a Monte Carlo simulation. Specifically, we ask what is the probability that ten peaks can be randomly scattered and yield ten "hits" to a periodic peak with interpulse. In one thousand Monte Carlo trials none demonstrated periodicity. In fact, on average, only four out of ten peaks could be fitted into a periodic pattern.

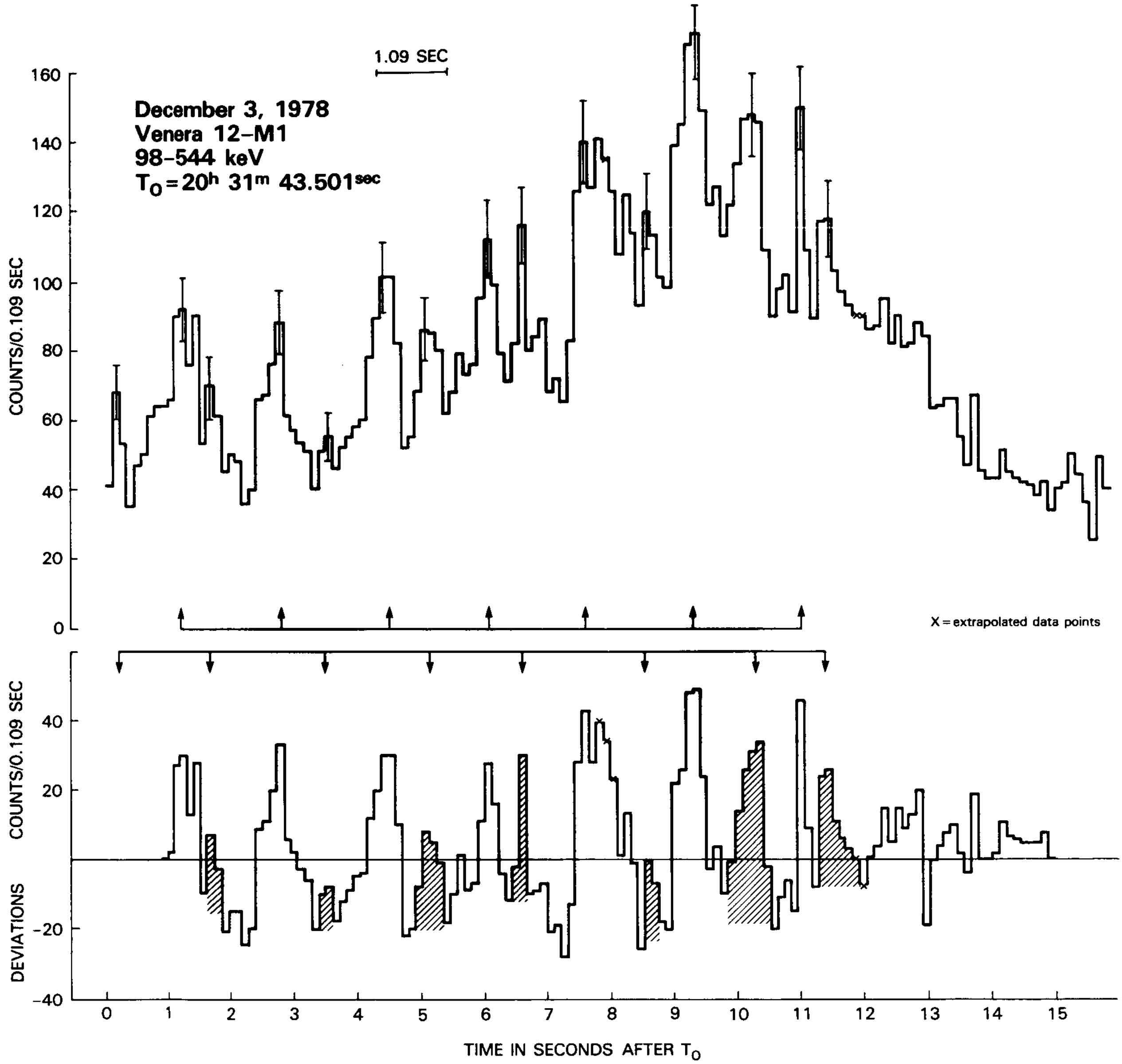

Figure 1. Time history of the December 3, 1978 event with the filtered variational part shown by the lower curve. Arrows indicate the 2 synchronized time series mentioned in the text.

The Event on 1969 November 6

A second event occurred on 1969 November 6 at 08^h38^m UT. Figure 2 shows the light curve with 109 ms resolution. The total duration of the event is about 10 s. There are three major features and three secondary features. The delay times between both series are indicated in Figure 2. The folded light curve of the pulse profiles is presented in Figure 4b with a time resolution of about 15 ms. Time variations down to 30 ms are seen in the average pulse profile. The initial rise occurs within 150 ms and the decay takes ~ 360 ms. The distribution of interval times between features is shown in Figure 5.

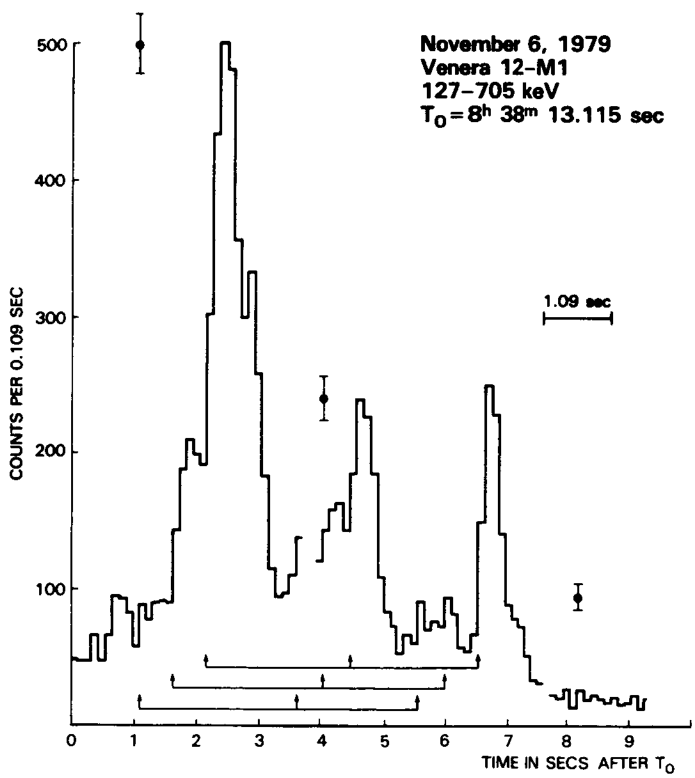

Figure 2. Time history of the November 6, 1979 event.

The Event on 1981 September 6

Another short event which shows well defined multiple pulse structure occurred on 1981 September 6 at 23^h53^m UT. Figure 3a shows the total event. A time-expanded view of both the initial low level and later high intensity multiple structures are shown in Figure 3b. There is a total of nine peaks with a characteristic time delay of ~ 2.5 s. The light curve could also be interpreted as repetitive groups of three peaks with a time delay of about 6 s. The successive light curves of these groups are shown in Figure 4c. This pattern is revealed at energies up to 300 keV. The distribution of interval times between features is shown in Figure 5.

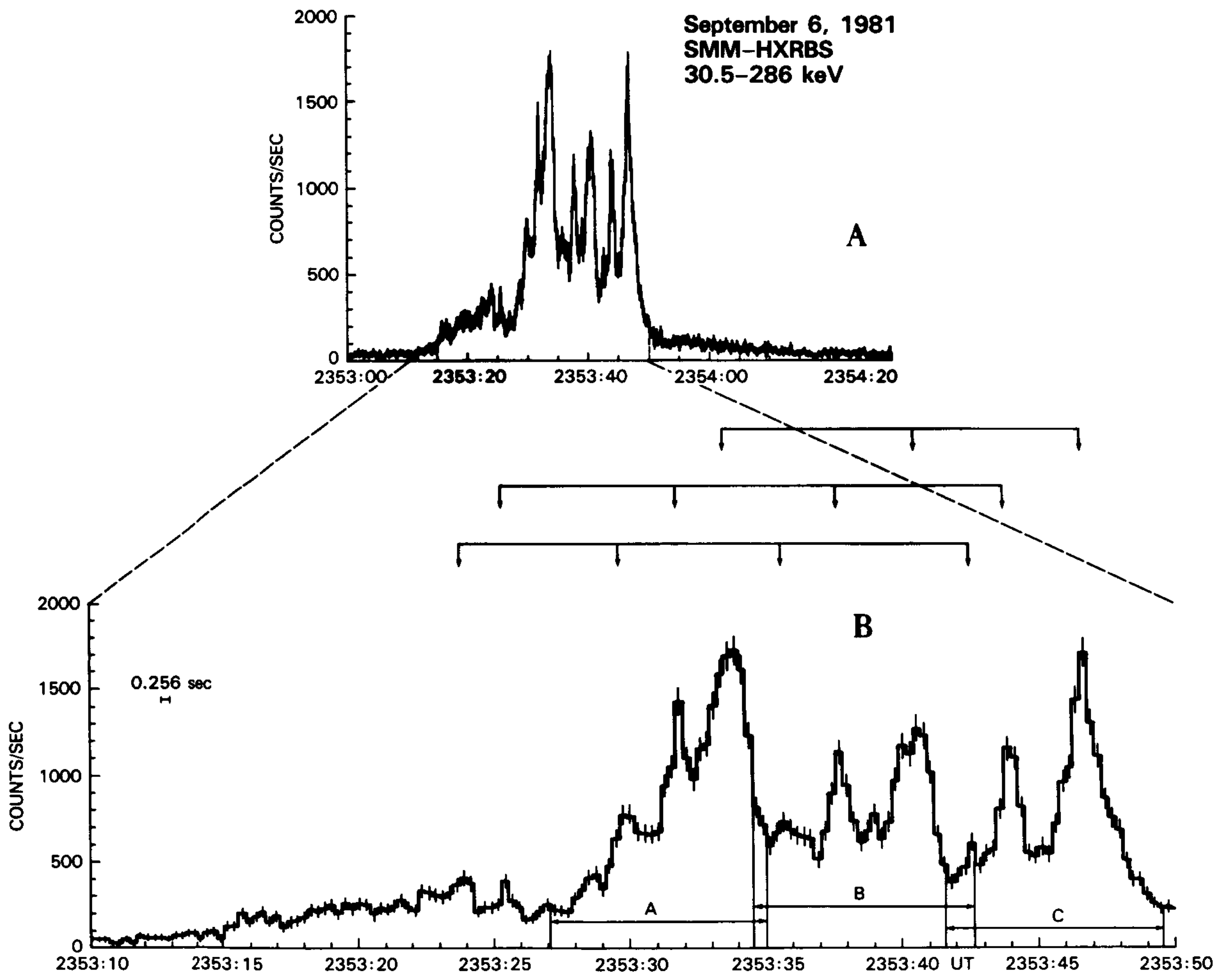

Figure 3. Time history of the September 6, 1981 event.

In order to evaluate the characteristic parameters of the repetitive features we have epoch-folded appropriate intervals of the light curves of events 1 and 2 and the results are shown in Figure 4a and 4b, respectively. The similarities of the features of the third event are revealed by the aligned profiles of Figure 4c.

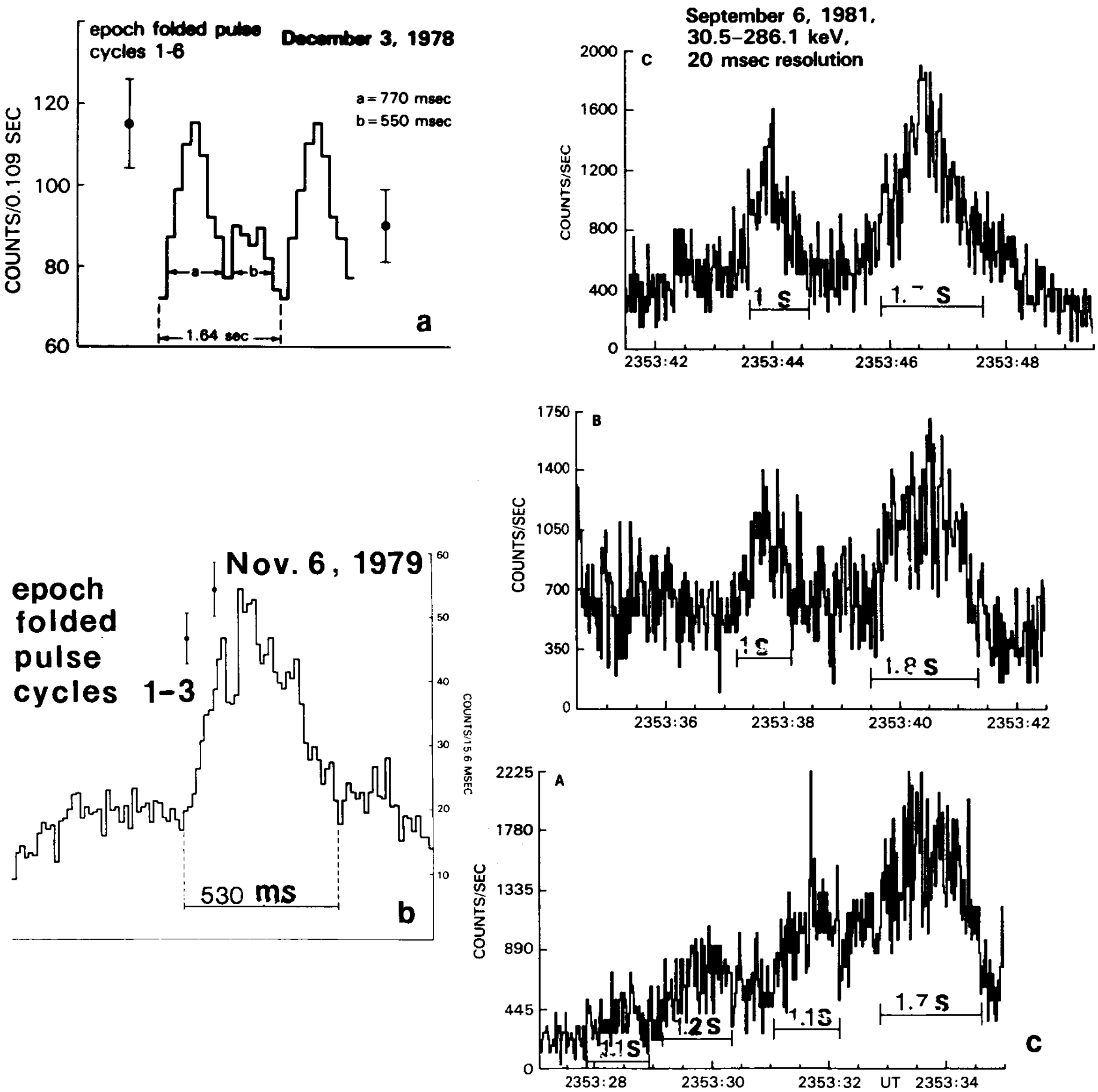

Figure 4. Common temporal aspects of the pulsed features of events 1, 2 and 3.

All of these events are short with total durations not exceeding 40 s. Significant features with widths of about a second are revealed as distinct peaks with persistant delays between them. The characteristic time delay for three events is 1.6 s, 2.3 s, and 6 s, respectively. Figure 5 shows the frequency distribution of these intervals for all 3 events.

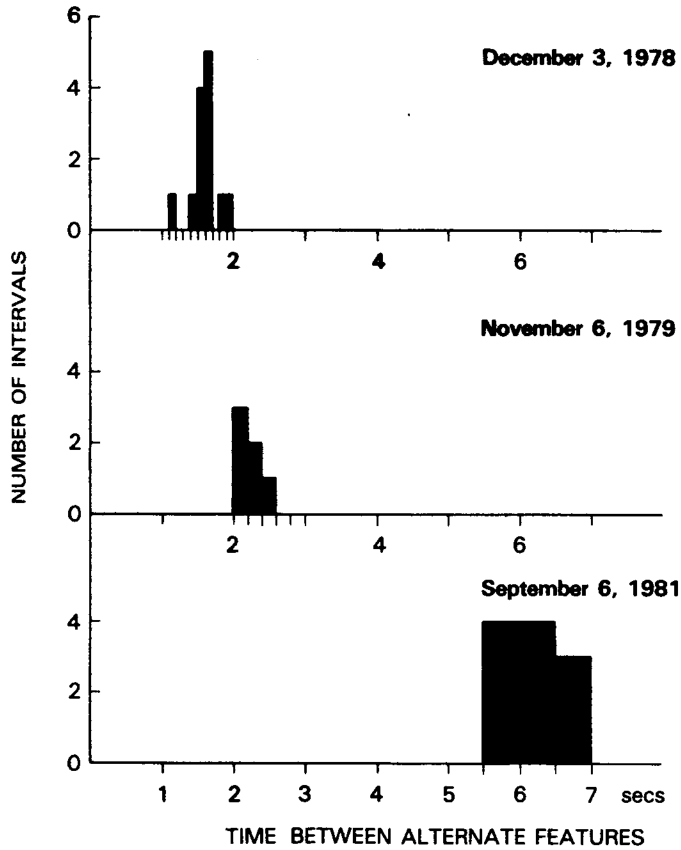

Figure 5. Frequency distribution of the alternate time intervals between significant features of the three events.

The ratio of the amplitude of the pulse ΔJ to the average intensity J is $\sim 50\%$. The pulses occur at energies up to 360 keV. The amplitude of the successive peaks of the December 3 event are nearly constant giving a high value of the quality Q of the assumed generating oscillator, where $Q = \pi t/P$, t is the e-folding time of the decrease in the pulse amplitude, and P is the pulse period. In Figure 6a,b, and c, we show the simultaneous behavior at various energies for all events.

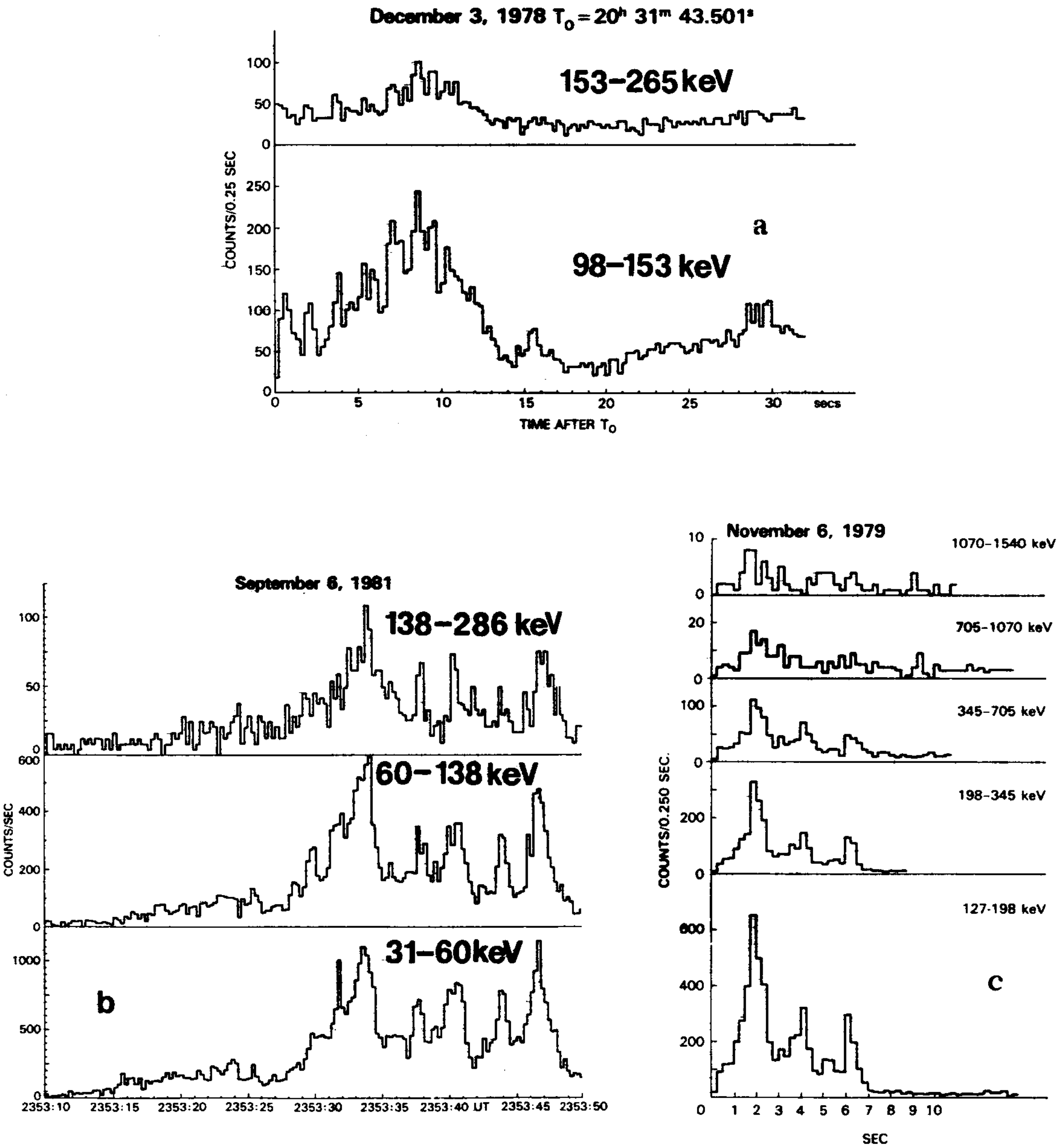

Figure 6. Time profiles at various energies for all 3 events.

We have studied the evolution of the X-ray spectrum for the event of September 6, 1981 with a time resolution of 256 ms. Figure 7 shows the spectral index A_2 of the best fitted power law along with the intensity profile of the event. At least three of the peaks are associated with lower power law index values indicating a harder spectrum than in the valleys. This type of behavior of spectral variation is also reported by Kosugi (1985) at this meeting.

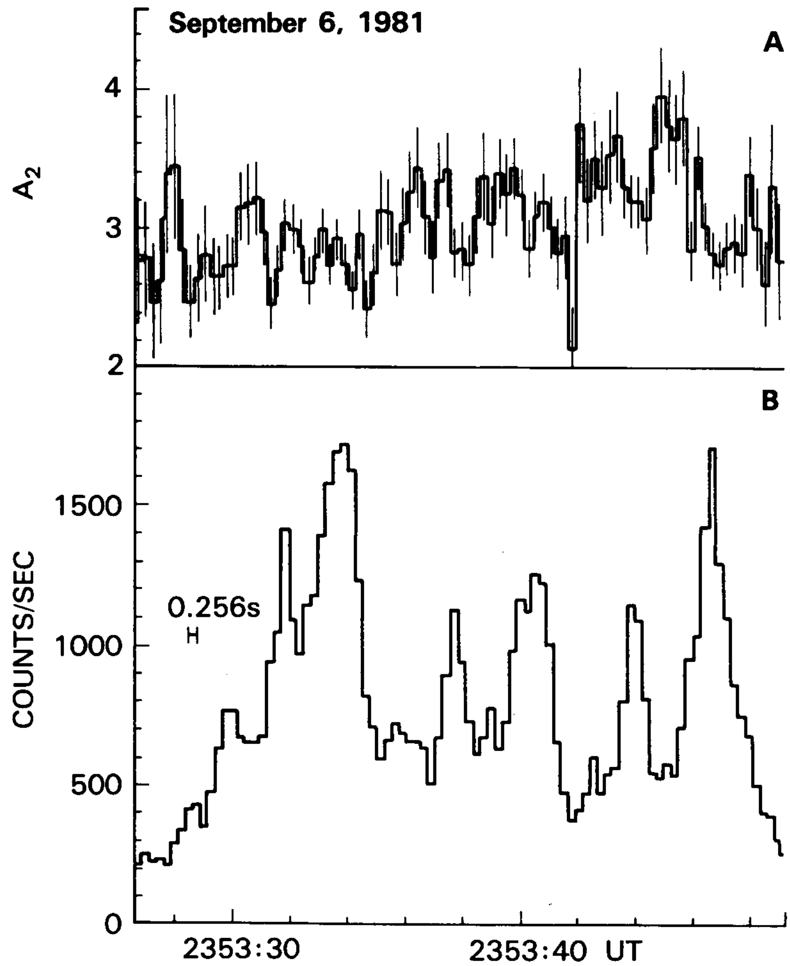

Figure 7. Temporal variation of the power law index A_2 and the HXRBS count rate for the event of September 6 in the energy range from 30 to 290 keV.

In the MHD model reported by Zaitsev and Stepanov (1982, 1984), compact ($\leq 10^{10}$ cm) magnetic loops with plasma density and electron temperature one or two orders of magnitude higher than the ambient values are considered as the resonators for fast mode MHD waves. The period P of fast magnetoacoustic oscillations in a loop with a radius r that is much smaller than the length is given by the following expression:

$$P = r(c_A^2 + c_s^2)^{-1/2}$$

where c_A is the Alfven speed and c_s is the sound speed. With r between 10^8 and 10^9cm and $(c_A^2 + c_s^2)^{1/2} \simeq 10^8$cm s^{-1}, one gets P in the range of 1-10s, in good agreement with our results. Values of the period P, the degree of modulation $\Delta J/J$, and the quality of the oscillator Q obtained from the observations enable estimations to be made of the plasma density, the plasma temperature, and the magnetic field strength in the loop (Zaitsev and Stepanov, 1982).

This type of analysis for the three events presented here indicates temperatures of $\sim 10^7$ K, magnetic fields of ~ 100 Gauss and plasma densities between 10^{10} and 10^{12}cm^{-3}. These are in general agreement with values of these parameters derived from other models.

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